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NASA Contractor Report 186010

A Guide to Structural Factors for Advanced Composites Used on Spacecraft

Robert Van Wagenen

CONTRACT NASW-4311
AUGUST 1989

(NASA-CR-186010) A GUIDE TO STRUCTURAL
FACTORS FOR ADVANCED COMPOSITES USED ON
SPACECRAFT (Vitro Corp.) 42 p CSCL 117

N92-20678

Unclass

63/24 0078200

NASA

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Prepared for
the National Aeronautics and Space Administration
under Contract NASW-4311



National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

1989

The use of composite materials in spacecraft systems is constantly increasing. Although the areas of composite design and fabrication are maturing, they remain distinct from the same activities performed using conventional materials and processes. This has led to some confusion regarding the precise meaning of the term "factor of safety" as it applies to these structures. In addition, composites engineering introduces terms such as "knock-down factors" to further modify material properties for design purposes.

This guide is intended to clarify these terms as well as their use in the design of composite structures for spacecraft. It is particularly intended to be used by the engineering community not involved in the day-to-day composites design process. An attempt is also made to explain the wide range of factors of safety encountered in composite designs as well as their relationship to the 1.4 factor of safety conventionally applied to metallic structures.

This guide to factors of safety for composites used in spacecraft was developed by Dr. Robert Van Wagenen, Vitro Corporation, under the direction of Dr. Michael Greenfield of the Systems Assessment Division, Office of Safety, Reliability, Maintainability and Quality Assurance.

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Associate Administrator for Safety, Reliability,
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LIST OF ACRONYMS AND ABBREVIATIONS

AIR	Aerospace Information Report
Al	Aluminum
AMS	Aerospace Materials Specification
ANSI	American National Standards Institute
ARP	Aerospace Recommended Practices
ASTM	American Society for Testing and Materials
C.V.	Coefficient of Variation
DA	Design Allowable
DLL	Design Limit Load
DODISS	Department of Defense Index of Specifications and Standards
DUL	Design Ultimate Load
ENVIR.	Environment
FAA	Federal Aviation Agency
FS	Factor of Safety
G-E	Graphite-Epoxy
HAG-5	Subgroup H, Action Group 5, The Technical Cooperation Program
HDBK	Handbook
JPL	Jet Propulsion Laboratory
K/D	Knockdown
MIL	Military
MS	Mean Strength
MSC	Material Sciences Corporation
NASA	National Aeronautics and Space Administration
OA	Operating Allowable
RESP.	Response
SACMA	Suppliers of Advanced Composite Materials Association
SAE	Society of Automotive Engineers
SDM	Strength Design Margin
SDM/MS	Strength Design Margin Ratio to Mean Strength

LIST OF ACRONYMS AND ABBREVIATIONS (CONT.)

SRV	Structural Response Variability
STR.	Strength
STRUCT.	Structural
SV	Strength Variability
TUL	Test Ultimate Load
VAR.	Variability

I. INTRODUCTION

A. PURPOSE

The purpose of the guide is to provide a basis for assessing the structural factors (factors of safety and knockdown factors) that are used for composite structures in spacecraft. This is done by reviewing their relationships with design approaches, design uncertainties, material strength properties, and testing methodology. The guide also summarizes the current status of efforts to develop uniform standards for composite material specifications, processing procedures, testing methodology, and failure analysis.

B. DEFINITIONS

Factors of Safety are load multiplication factors that are applied to the maximum expected operating load (or design limit load) to provide a design ultimate load for conservative structural design. Knockdown Factors are strength reduction factors that are applied to the material mean strength to account for variations in material composition, service environment, and structure geometry. Usually, a combination of both types of factors is used for the design of advanced composite structures in spacecraft. In many cases, the factor of safety includes the effects of one or more knockdown factors.

In the most general sense, advanced composites consist of reinforcing fibers embedded in a metal, ceramic, or resin matrix to achieve properties for the combined materials that are superior to either the reinforcement or matrix material taken separately. However, for this guide, the term advanced composites (or composites) implies graphite or Kevlar fibers embedded in a thermosetting or thermoplastic resin matrix. (On current aircraft and spacecraft, the most frequently used combination is graphite fibers and epoxy resin.)

Also, because of the nearly linear relationship between composite stress and strain, the term material strength (or strength) will be used in this guide to indicate, usually without any clarifying distinction, either the maximum stress that can be sustained by the composite material, or the strain level existing under the maximum stress condition.

The expression design allowable (or static design allowable) will be used in this guide to designate the allowable material strength for structural design under static loading conditions. The design allowable is established from coupon test data and can vary greatly for the same material and application, depending upon how much conservatism has been incorporated as a result of testing and analytical methods, strength limit definition, and knockdown factors.

Additional terms are defined in the Glossary.

C. OVERVIEW

Advanced composites possess a number of special properties that make them the material of choice for many aerospace applications. These properties include: high specific strength and stiffness, superior resistance to fatigue and corrosion, very low coefficient of thermal expansion (good dimensional stability), and low thermal conductivity. In addition, since the reinforcing fibers provide most of the strength and stiffness, they can be selectively oriented to bear the expected loads, giving composites a major advantage over metals.

However, composite reinforcing fibers possess low toughness (low ductility). Therefore, the fact that the fibers provide most of the strength also results in a major disadvantage; composites exhibit a brittle, unforgiving behavior when stressed to failure.

Another major disadvantage of composites is the high variability of their static strength and fatigue life for the same types of material. This is primarily due to the random nature of the composite failure process, which results from one or a combination of the following conditions: microcracking, delamination, fiber failure, or local buckling of fibers and lamina. (This is in contrast to the formation of a critical flaw in metals, which leads to crack growth and fracture.)

Additional factors influencing composite variability are: nonstandard material specifications for the fibers and resins; nonuniform processing techniques; and variance in testing methods, particularly for compression, bearing, and impact loading.

The failure of composite structures is much less predictable than for metal structures. This is due to the random, multifaceted nature of the composite failure process; and because the composite structures have greater material and fabrication complexity. As a result, composite structures require more conservative factors of safety and knockdown factors, more complex analytical methods, and more extensive test programs. A strength or fatigue analysis must consider: fiber type and material, matrix material, fiber directions, lamina lay-up, processing cycle, applied load combinations, temperature, moisture content, fiber volume, and discontinuities such as holes and impact damage.

Since advanced composites are relatively new, methods of testing and analysis are still evolving and vary from company to company and even among projects. Substantial disagreement exists on what constitutes a structural failure and how to predict it. Failure definitions and failure criteria differ radically; resulting in a wide range of material strength values, knockdown factors, and factors of safety. There is a clear need to develop improved standards for material specifications, processing procedures, testing methodology, and failure mode analysis.

II. DESIGN METHODOLOGY

A. STATIC LOADING CONTROLS MOST SPACECRAFT DESIGN

As mentioned, several basic differences exist between composites and metals that require more conservative factors of safety and knockdown factors for composite structures. An additional difference that is important to the determination of structural factors for spacecraft is the behavior of composites (relative to metals) under static and fatigue loading conditions.

Under static or low-cycle loading conditions, composites are much more notch-sensitive than metals, both in tension and compression. This is due to the brittle nature of the reinforcing fibers. However, under high-cycle (fatigue) loading conditions, the reverse is true. Composites become much less notch-sensitive than metals, exhibiting little difference between notched and unnotched residual strength levels. This reversed behavior is the result of high-cycle failure modes (such as delamination) occurring before fiber failure.

Therefore, composites require a large material strength knockdown for static or low-cycle notch sensitivity, but no appreciable strength knockdown for high-cycle notch sensitivity. However, for high-cycle life, composites do require a large strength knockdown to account for the many failure modes associated with repeated or reversed out-of-plane loading. In comparison to metals, composites require larger total strength knockdowns to account for low-cycle fatigue behavior, but smaller total strength knockdowns to account for high-cycle fatigue behavior.

Since maximum structural loading conditions for spacecraft occur on an infrequent basis, the static or low-cycle loading condition controls most structural design. Therefore, this guide focuses on the material properties, analysis and testing methodologies, and structural factors that affect static or low-cycle-life design. It should be noted that the difference in behavior between composites and metals under fatigue loading may influence the design of structures that use both materials, if thermal cycling stresses are significant (in magnitude and frequency) and/or joining conditions (bolted or bonded) are critical design features.

The degradation of material properties with time (for both composites and joint adhesives) may also be an important design consideration.

B. RELATIONSHIP OF FACTORS WITH DESIGN APPROACH

The composite structural factors vary in number and magnitude according to the selected design approach. As indicated by Figure 1, there are four generally accepted approaches that may be used for applying structural factors to the composite static design problem.

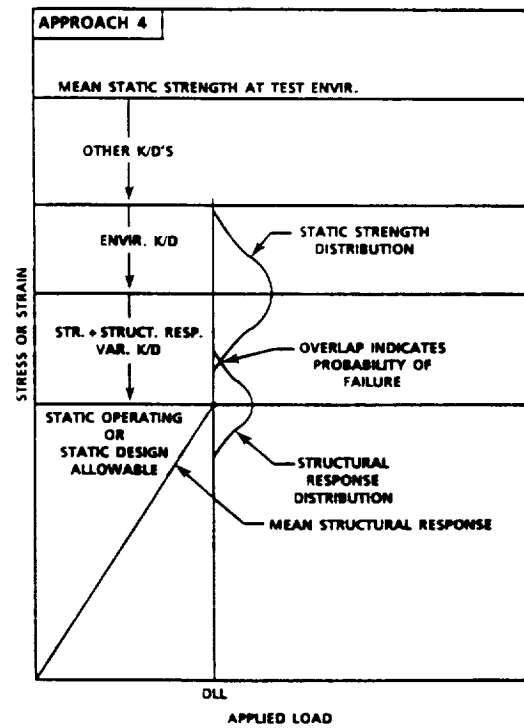
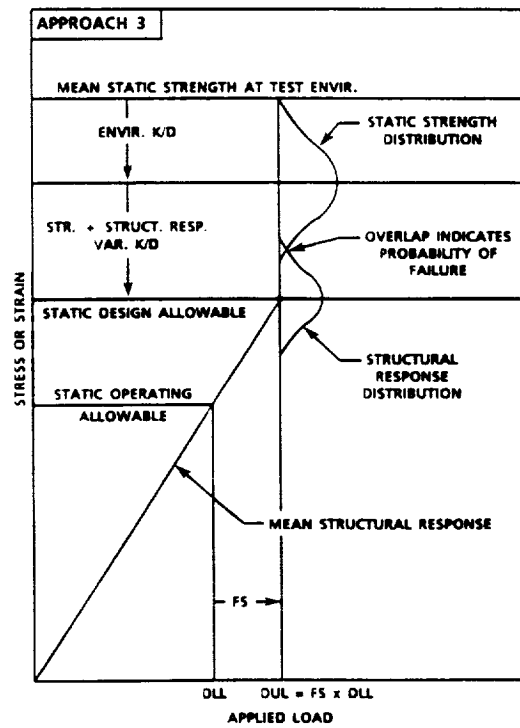
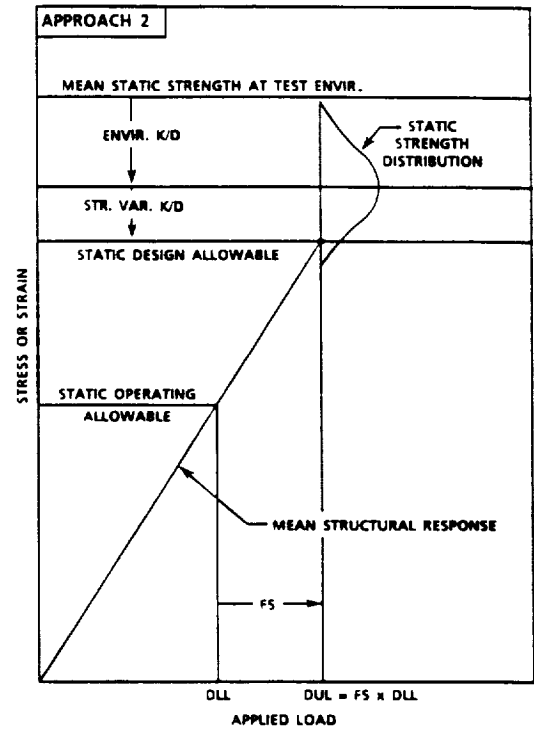
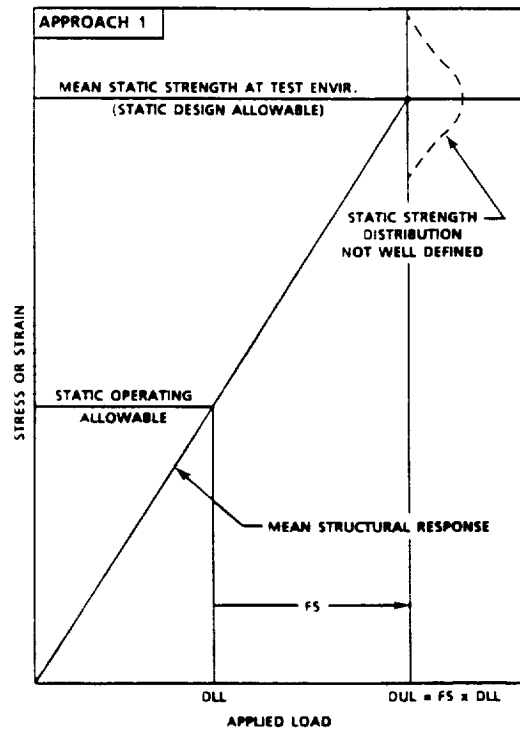


Figure 1. Four Static Design Approaches

- Approach 1 Include all uncertainties for such factors as material, environment, structure, loading, and analysis in a single factor of safety; and use no knockdown factors. The design allowable is then set equal to the mean strength (or its strain equivalent) for the test environment. This approach is applicable when there is a high degree of uncertainty about material strength properties because of an inadequate data base. It has the disadvantage of requiring a large factor of safety and, therefore, conservative structural design. Because design verification is difficult, this approach should not be used for flight-critical structures.
- Approach 2 Use a factor of safety to account for the less well-known effects of structure, loading, analysis, and damage uncertainties; and two mean strength knockdown factors to account for the usually better known effects (derived from testing) of environment and strength variability. The design allowable is then set equal to a strength level that has been "knocked down" from the mean by both factors. This is a more standard approach. It provides a significant reduction in the unknowns associated with the design process, since strength variability and environmental effects are two major influences on composite strength. However, it does require extensive testing, especially if the influence of environmental effects on full-scale failure modes are to be included.
- Approach 3 Use the same number of structural factors as for the second approach, but include the effect of structural response variability (stress or strain differences caused primarily by fabrication tolerances) in a mean strength knockdown, rather than in the factor of safety. For this approach, the effects of strength variability and structural response variability are combined into a single knockdown factor. The design allowable is then set equal to a strength level that has been "knocked down" from the mean by this combined factor as well as by an environmental factor. Since the structural response variability is determined from test data, this approach has the advantage of removing additional design uncertainty; but the disadvantages of requiring significant strain gage instrumentation, and for best results, environmentally conditioned components.
- Approach 4 Apply a sufficient number of knockdown factors to the mean static strength to account for all unknowns, including those associated with loading and analysis. Then, in principle, the factor of safety could be set equal to 1.0, making the static operating allowable equal to the design allowable, as shown in Figure 1. However, in actual practice, a minimum value of 1.5 is generally used for the factor of safety to provide additional conservatism. This is a less standard approach.

C. APPLICATION OF FACTORS TO STATIC DESIGN PROCEDURE

A review of the general static design procedure for composite structures serves to illustrate the use of structural factors in the design process. A description of this procedure also indicates the significant dependence of the factors on coupon, component, and full-scale test data. In addition to defining material strength properties, knockdown factors, and the design allowable, the test data also strongly influence the design approach.

The basic steps for the general static design procedure can be summarized as follows (refer to Figure 1, Approach 3):

1. A structural design approach is selected based on the number and the type of available knockdown factors and the desired conservatism for the factor of safety. This decision is primarily a function of the availability and quality of test data.
2. A mean static strength and strength variability distribution are defined for the structural material (in terms of stress or strain), based on coupon-level testing under nominal and off-nominal environmental conditions (see Section III.A).
3. Mean strength knockdown factors for strength variability and in-service environmental effects are determined from the coupon data; a mean strength knockdown factor for structural response variability may also be determined from component and full-scale tests.
4. A design allowable is established for the structural material at a strength level that is far enough below the coupon mean strength (for the test environment) to account for one or more of the following effects: service (or operating) environment, strength variability, observed structural response variability, and other uncertainties; by applying appropriate knockdown factors.
5. The structure is designed or sized so that the design limit load (DLL) multiplied by the desired factor of safety (FS), which is the design ultimate load (DUL), results in a mean structural response (stress or strain) that is equal to the design allowable.

For design Approach 3 or 4, the design allowable is established at a stress or strain level that permits some overlap between the levels of maximum structural response and minimum material strength. This is acceptable because the resulting combined probability of failure will still be sufficiently low. Also, although the design limit load and ultimate load are treated as static loads, they are really maximum values for the applied loads. Therefore, under actual in-service loading conditions, the overlap

between structural response and material strength distributions, or the probability of structural failure, will be reduced even further as a result of the statistical nature of the applied load.

D. VARIATION OF FACTOR OF SAFETY WITH DESIGN ALLOWABLE

For composites, the design allowable values are established from coupon-level strength data and the statistical analysis of these data, but can show large variations for three reasons:

1. Differences in coupon configuration and preparation, testing approach, failure definitions, and failure criteria can lead to substantially different strength limits and design allowables for the same material and application. An article by Burk (Reference 1) indicates that during 1983 at least two testing approaches, three failure definitions, and eight failure criteria were being used to define composite material strength under static loading conditions.
2. The minimum strength limits for composites (and metals) are defined from the coupon data in terms of A-basis reliability (i.e., defined as that strength level which 99 percent of a set of test specimens will exceed with a 95 percent confidence); B-basis reliability (i.e., defined as that strength level which 90 percent of the specimens will exceed with a 95 percent confidence); or in some cases, a percentage of mean strength. Therefore, the design allowable will also vary with the specified minimum strength requirements. For example, Lincoln (Reference 2) indicates that the Federal Aviation Administration requires the use of A-basis strength values for the design of single-load-path composite structures, but allows the use of B-basis strength values for redundant-load-path composite structures.
3. As indicated earlier, the design allowable values can exhibit large differences, depending on whether or not they include knockdown factors for environmental effects, strength variability, structural response variability, or other uncertainties.

Therefore, the factor of safety can vary greatly for the same material and application, depending upon how much conservatism is included in the design allowable as a result of testing and analytical methods, strength limit definition, and knockdown factors. The greater the conservatism, the smaller will be the required factor of safety. If the design allowable has enough conservatism, the factor of safety can be set equal to 1.0, which is the same as eliminating the concept of having a load-based factor of safety.

III. TESTING METHODOLOGY

A. DESIGN DEVELOPMENT TESTS

As has been indicated earlier, the strength properties of composites depend on many parameters (such as temperature and humidity) and also can vary substantially with material specifications and processing procedures. Therefore, the design of composite structures relies heavily on testing. Depending on the complexity of the structure, this testing is carried out at several levels to define the allowable design stress (or strain) and failure modes according to a "building-block" approach. Such an approach relies on coupon, element, subcomponent, and component level tests to reduce the number of full-scale structural tests required for design verification; by applying a statistical interpretation to the data obtained from the smaller-scale tests. The number of tests decreases from coupon level to component level.

1. Coupon Tests (also referred to as Design Allowable Tests) - Conducted at the lamina level (specimen with unidirectional fibers) and at the laminate level (specimen with multidirectional fibers or fabric plies) to establish mean strength and strength variability distribution. Test parameters include loading mode (tension, compression, shear) and environment (temperature, moisture).
 - a. Lamina-level tests are used to determine mechanical properties such as tensile and compressive ultimate strength, modulus of elasticity (longitudinal and transverse), shear modulus, and Poisson's ratios. These tests should include longitudinal, transverse, and 45-degree loading relative to fiber direction.
 - b. Laminate-level tests are used to evaluate the combined impact of processing and design variables on the strength properties of a multidirectional or fabric lay-up. An example is the testing of fiber-dominated lay-ups versus matrix-dominated lay-ups using specimens containing open holes, filled holes, and no holes (unnotched). Special laminate-level tests are also used to evaluate the damage resistance of composite materials.

A relatively large number of tests are required to establish A-basis or B-basis statistics for different loading modes, failure modes, and environments. For A-basis reliability, a report by Whitehead, Kan, Cordero, and Suether (Reference 3) recommends that 30 coupon tests be conducted under the worst-case environment for each loading or failure mode. For B-basis reliability, this number decreases to 15. In contrast, MIL-HDBK-17B (Reference 4) recommends that 30 coupon tests be used to establish B-basis reliability and does not currently address A-basis reliability.

2. Element/Subcomponent Tests - Conducted to determine primary failure modes. Reference 3 indicates that as many as six tests may be required for each failure mode being investigated under selected worst-case environments. Examples of failure modes at this level are laminate failures and hole-bearing failures at mechanical joints, and bondline failures at bonded joints. Results of these tests are used to predict full-scale failure modes. This procedure is the weakest link in the "building-block approach" because of the inherent sensitivity of composite structures to out-of-plane secondary loads.
3. Component Tests - Conducted to demonstrate: the variability in structural response; and more complex failure modes, including primary failure mode interactions. Reference 3 indicates that a minimum of three identical specimens are required for this test, but that they do not all have to be for the same environmental condition, since the structural response variability is relatively independent of environment.

In addition, by assuming that this variability is also independent of structural complexity and loading condition, the component test data can be pooled with data from element and subcomponent tests to provide a larger data base for determining the structural response variability statistics. In cases where the effect of structural response variability is to be included in a knockdown factor for the mean strength, a combined reliability based on both structural response variability and strength variability should be used (refer to Section IV.C).

B. DESIGN VERIFICATION TESTS

At the request of the Johnson Space Center, McDonnell Douglas Astronautics Company (Houston) has surveyed a large number of companies and organizations to gather information on acceptance testing for bonded composite structures in the aerospace industry. This material was collected to support the determination of testing requirements for Shuttle payloads that use composite materials for primary structures. It has been assembled into a single document (Reference 5), which contains information and opinions from over 25 experts at NASA Centers and support contractors. Many of the ideas expressed in this reference document have been reflected in the following summary as well as in the Conclusions (Section VI) to this guide.

Whenever possible, one or more full-scale tests should be conducted to verify the complete structural design. If more than one full-scale structure is available, it may be tested to failure to confirm the failure modes analysis. For a structure that has been well-defined at the "building-block" test levels, the minimum acceptable failure load is the design limit load (DLL) times the factor of safety, which is the design ultimate load (DUL).

Two levels of full-scale testing may be used for composite structures, depending on the size of the data base and the criticality of the component:

1. Design verification tests conducted at DUL for components that will not be flown. (In some cases, these tests are conducted at even higher loads to induce failure.)
2. Acceptance and/or proof tests conducted at 110 to 125 percent of DLL for the first component that will be flown, and conducted at DLL for subsequent components that will be flown.

Most NASA and support contractor experts recommend the testing of full-scale components and structures to failure for design verification, whenever possible. The Jet Propulsion Laboratory (JPL) does not agree with this viewpoint, however, indicating that a test to destruction is too expensive and does not uncover manufacturing defects in the flight hardware. To circumvent this difficulty, JPL (and other organizations) recommend using higher factors of safety in design, and higher load levels for proof tests.

One of the concerns related to the JPL viewpoint is that unanticipated critical design details in full-scale articles, which are not evaluated thoroughly in subcomponent test, may cause failure of the flight article. Because of this uncertainty it is not clear what factor of safety is acceptable. The issue related to manufacturing defects in flight hardware should be the focus of NDE and/or proof test qualification, and be reflected as far as possible in design allowables.

The Air Force uses 110 percent of DLL for acceptance tests and proof tests of first components, which is the same value that they use for metals. The Johnson Space Center prefers to use 120 percent of DLL, because of the greater variability of composites. This higher value has been proposed for proof tests in the NASA Fracture Control Handbook for Shuttle payloads (Reference 6). Several design specialists question the value of conducting proof tests on composite structures, because a proof test does not produce crack retardation as in metals, but can produce undetected damage in a flight structure (Reference 5).

Certification procedures for composite structures used on aircraft are described in Reference 2. The static testing portion of these procedures should be applicable to spacecraft flight-critical structures and can be summarized as follows:

1. The Federal Aviation Administration requires the composite structure to survive a static test to DUL, after it has been subjected to some type of undetectable damage from a realistic event, such as impact from a dropped tool. This test may be performed without environmental conditioning when there is component test data for establishing a knock-down factor for the worst-case service environment. The test program should also include the effects of long-term environmental exposure on material properties.

2. The U.S. Navy currently requires that the composite structure, after receiving visually apparent damage, have its ultimate load (DUL) capability verified by a full-scale static test. The Navy allows this test to be conducted on structures that have not been environmentally conditioned, but requires an environmental knockdown of the demonstrated load capability based on the results of a component testing program.
3. The U.S. Air Force considers a full-scale static test to DUL as essential for verification of the composite structure. This test may be performed without environmental conditioning only if the design development tests demonstrate that a critical failure mode is not introduced by the environmental conditioning. A test of the composite structure to failure is a program option. The capability of the composite structure to tolerate damage is normally verified by design development tests.

A report on the certification of composite aircraft structures by HAG-5 (Reference 7) indicates that static strength verification can be accomplished under ambient conditions, without prior environmental exposure, by using one of two full-scale test methods.

1. Increased Loads Approach - For this approach, two sets of design allowables are generated; one for the ambient test environment, and the other for the worst-case service environment. An "increased loads factor" is then defined as the ratio of the ambient mean static strength to the worst-case mean static strength. This factor is applied to the DUL along with a variability factor to determine the test ultimate load (TUL). If the structure fails at a load lower than the TUL (while under ambient conditions), a redesign is required. This approach minimizes the possibility of missing high stress spots, but may overtest metal parts in structures which are a combination of composites and metals. It may also miss failure modes that are a function of environmental degradation.
2. Knockdown Strain Approach - This approach is the inverse of the Increased Loads Approach, and again requires two sets of design allowables. A "knockdown strain factor" is defined as the ratio of the environmentally degraded mean failure strain to the ambient mean failure strain. An ambient design allowable is then reduced by this factor to determine an allowable strain value for the test. If under DUL and ambient test environment any measured strain exceeds its allowable test value, failure is deemed to have occurred and some redesign of the structure is necessary. This approach prevents the overtesting (or overdesigning) of metal parts in structures that are a combination of composites and metals, and provides an excellent check on structural stress analysis. However, it may miss high stress spots as well as environmentally affected failure modes.

Neither approach is as reliable as performing a full-scale structural test for the worst-case service environment, but the complexity and expense of such a test makes either the Increased Loads Approach or the Knockdown Strain Approach an attractive alternative. The HAG-5 report makes no recommendation on which approach to use, but does conclude that environmental effects are more important than variability effects.

IV. STRUCTURAL FACTORS

A. BASIS FOR SELECTING VALUES

As indicated in Section II.B, structural factors are used in the design process to safely account for:

- Uncertainties in analytical methods, including the prediction of failure modes for full-scale structures.
- Unintentional deviations from service load and service environment.
- Variability in structural response (differences in stress or strain level at the same location in supposedly identical structures for the same applied load).
- Manufacturing flaws and in-service damage.
- Variability of material strength.
- Effects of environment (such as temperature, moisture, and ultraviolet light).
- Effects of structural geometry (such as shape, holes, and fillets).

Traditionally, a factor of safety has been used to account for the first four of these unknowns, while knockdown factors have been employed for the last three. Several other combinations have also been used, including factors of safety that account for all or none of the listed unknowns, depending on the conservatism of the design allowable (see discussion in Section II.D). In some cases the knockdowns for strength variability and environment are included in a single factor, if the strength data also include the effects of temperature and moisture over the range of the intended service environment. In addition, the effects of structural response variability and strength variability can be combined into a single knockdown factor as an alternative to including structural response variability in the factor of safety. (This was done in Reference 3).

In the case of metals, the traditional factor of safety values have been 1.5 for aircraft and 1.4 for spacecraft. These factors provide 95 percent confidence reliabilities that exceed A-basis allowables by a comfortable margin, because metals have low strength variability and exhibit a yielding (forgiving) behavior prior to failure.

For composites, more conservative factors of safety plus knockdown factors are used. This is primarily a result of design engineers having less confidence in their ability to predict material and structure behavior. Due to this reduced level of confidence, and to allow for other uncertainties, such as manufacturing flaws and in-service damage, most designers want a factor of safety of at least 1.5. This is after knockdown factors

have been incorporated into to the design allowable for environmental effects and strength variability.

However, a factor of safety of 1.5 is acceptable only if the material properties have been defined in a rigorous manner (e.g., according to MIL-HDBK-17 or to procedures in that handbook); and only if design verification is by full-scale testing to failure. If full-scale testing is not to failure, the factor of safety generally is increased by about 50 percent (to 2 or 2.25); and if in addition, the test data base is not adequate as defined above, the factor of safety is increased by 100 percent (to 3).

For the design of bolted joints, the European Space Agency's Composite Design Handbook (Reference 8) indicates that the design ultimate load (which already includes a factor of safety) should be increased by a factor of 2.

Methods for determining the mean strength knockdowns to be used with loading conditions that produce the bending or buckling of cylindrical shells are also provided by Reference 8. These knockdowns can be as large as 70 or 80 percent, even for B-Basis reliability.

Representative values for graphite-epoxy strength variability knockdown factors, both with and without the effects of structural response variability, were estimated in Reference 3, and are discussed below. These knockdown factors will be used in Section IV.D to examine the relative conservatism of the graphite-epoxy factor of safety values that are listed above.

B. KNOCKDOWN FACTORS FOR STRENGTH VARIABILITY

Calculated A-basis and B-basis knockdown factors for graphite-epoxy strength variability are listed in Reference 3 for several magnitudes of strength variability. These factors were developed by using the two-parameter Weibull distribution to describe strength variability (or reliability) in terms of a cumulative probability-of-survival function.

The Weibull (probability) density function is a two-parameter function of the form:

$$f(x) = (\alpha/\beta)(x/\beta)^{\alpha-1} \exp[-(x/\beta)^\alpha]$$

where: x is the independent variable, α is the shape parameter, and β is the scale or "characteristic life" parameter.

The Weibull density function is appealing for describing many failure and wear-out processes because of the many possible shapes that the two-parameter family of curves can assume. For example: when $\alpha = 3.44$, the resulting curve is approximately normal; and for $\alpha = 1.0$, the distribution is of the random exponential type. As the

shape parameter increases, the spread of the curve decreases, and thus failures based on the independent variable x (e.g., x represents "time" or "load") become more predictable.

The Weibull failure distribution (or cumulative probability distribution) is the integral of the density function. Its value, at a specified value x_0 , represents the probability of failure for x less than or equal to x_0 . This distribution can be expressed as follows:

$$P(x \leq x_0) = 1 - \exp[-(x_0/\beta)^\alpha]$$

In the present application, use of the Weibull failure distribution is motivated by the following: viewing the independent variable x as the applied load, with a Weibull model it will follow that the conditional probability of failure at a load x_0 , given survival (non-failure) up to x_0 , will increase as x_0 gets larger. This is the so-called "wear out" property and more explicitly, in the present context, means that for a test specimen which has not yet failed, each incremental increase in load yields a higher probability of failure.

For describing material strength variability, the Weibull cumulative probability-of-survival function is more appropriate. This function is equal to one minus the cumulative probability-of-failure function, and is defined on Figure 2. As indicated by this figure, the cumulative probability-of-survival function can be used to define non-dimensional strength values for any required level of survival or reliability. These values represent knockdown factors for mean strength to achieve a required reliability level for a material of given strength variability.

Figure 2 also demonstrates how the magnitude of the variability (or scatter) is characterized by the value of the Weibull shape parameter and has an inverse relationship to it; the larger the scatter, the smaller the Weibull shape parameter. Therefore, at a given level of reliability, the value of the knockdown factor will depend on the magnitude of the variability (or shape parameter) as well as on the size of the confidence interval.

Two sets of knockdown factors from Reference 3 are shown in Table I. The first set was based on the modal value of 20 for the Weibull shape parameter from several data sets and therefore represents the most probable or "best" estimates for the variability knockdown factors. The second set was based on a shape parameter value of 10, which is near the minimum value of the shape parameter from the same data sets, and therefore represents conservative estimates for the knockdown factors. A-basis factors were determined for a sample size of 30, while B-basis factors were based on a sample size of 15.

COMPOSITE STRENGTH RELIABILITY CAN BE DESCRIBED IN TERMS OF THE CUMULATIVE PROBABILITY-OF-SURVIVAL FUNCTION FOR THE TWO-PARAMETER WEIBULL DISTRIBUTION AS FOLLOWS:

$$P(X_{\text{FAIL}} \geq X) = e^{-(X/\beta)^\alpha} = e^{-\left[\left(\frac{X}{\bar{X}}\right) \Gamma\left(\frac{\alpha+1}{\alpha}\right)\right]^\alpha}$$

WHERE: X = STRENGTH (STRESS OR STRAIN)
 α = SHAPE PARAMETER
 β = SCALE PARAMETER

\bar{X} = MEAN STRENGTH
 $= \beta \Gamma\left(\frac{\alpha+1}{\alpha}\right)$

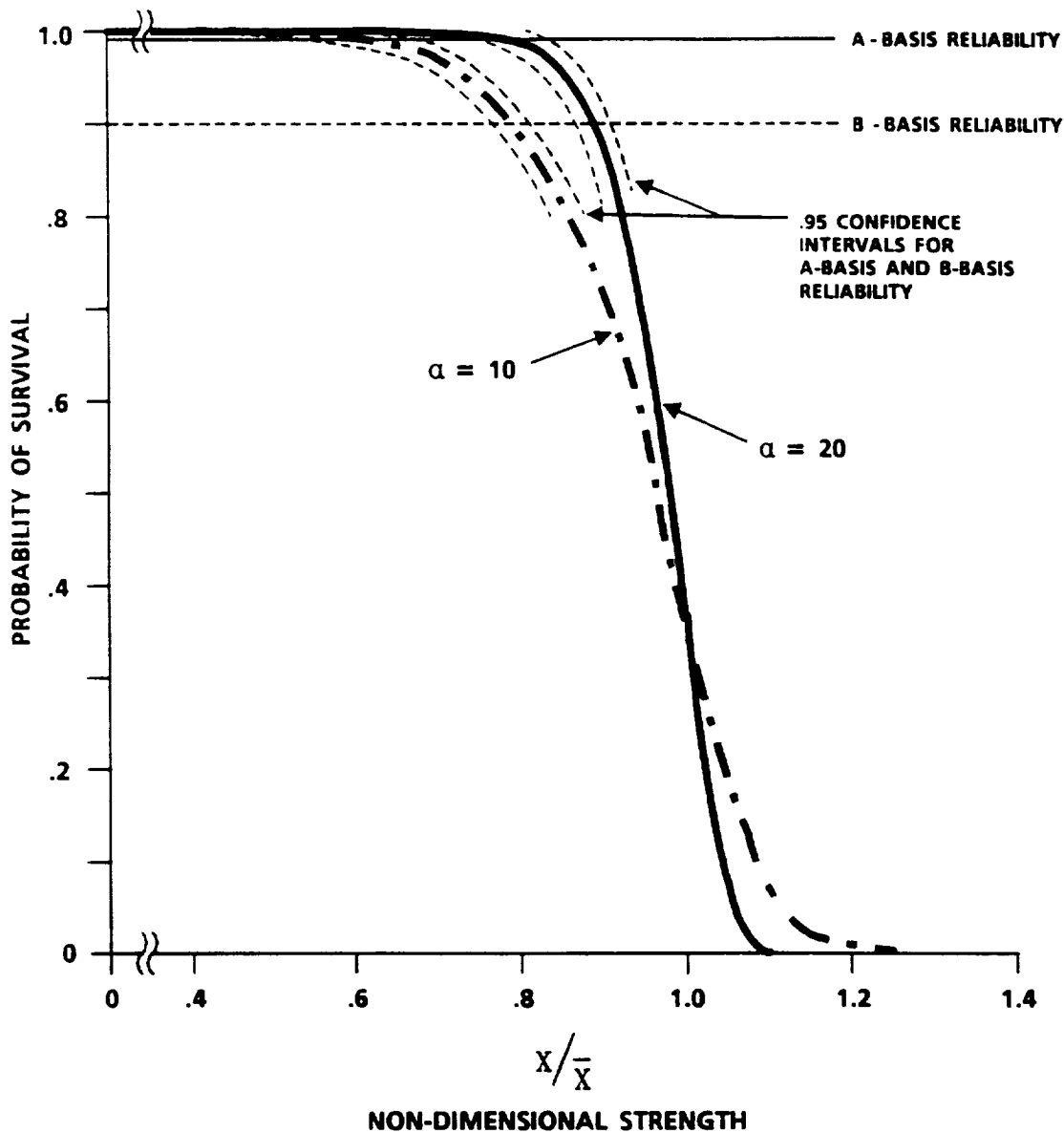


Figure 2. Composite Strength Reliability Based on the Weibull Distribution

TABLE I
STRENGTH VARIABILITY KNOCKDOWN FACTORS FOR GRAPHITE-EPOXY

Weibull Shape Parameter	Coefficient of Variation	A-basis K/D Factor	B-basis K/D Factor
20	6%	.805	.901
10	12%	.645	.808

K/D - Knockdown

In addition to listing the Weibull shape parameter as an indication of strength variability, the more familiar coefficient of variation (standard deviation/mean) has also been included in Table I. The relationship between the coefficient of variation (C.V.) and the shape parameter for the Weibull distribution is defined by Figure 3.

The strength variability of composites is greater than that of metals. This difference is reflected in the values of the Weibull shape parameter for the two materials. For example, a representative shape parameter for aluminum is 25, indicating less data scatter (strength variability) than for graphite-epoxy, where the modal value is 20. Therefore, composites require larger mean strength knockdowns for strength variability than metals (smaller knockdown factors) to provide the same reliability.

By making use of Figures 2 and 3, estimates can be made for A-basis and B-basis knockdown factors for the strength variability of metals by assuming that their coefficient of variation is in the range of 3 to 5 percent. These estimates are listed in Table II. A comparison with Table I shows that metals are affected less by strength variability than composites, especially for A-basis reliability. The calculation procedure for the knockdown factor is illustrated by the following example, where the C.V. is 5 percent and an A-basis reliability is required.

For a C.V. of 5 percent, Figure 3 is used to select a corresponding Weibull shape parameter of 25. Then this value of the shape parameter is substituted into the equation for the cumulative probability-of-survival function (see Figure 2) to give:

$$\begin{aligned}
 P &= \exp\{-[x/\bar{x}]\Gamma[(25+1)/25]\}^{25} \\
 &= \exp\{-[x/\bar{x}][.97844]\}^{25}
 \end{aligned}$$

or,

$$\ln P = -\{[x/\bar{x}][.97844]\}^{25}$$

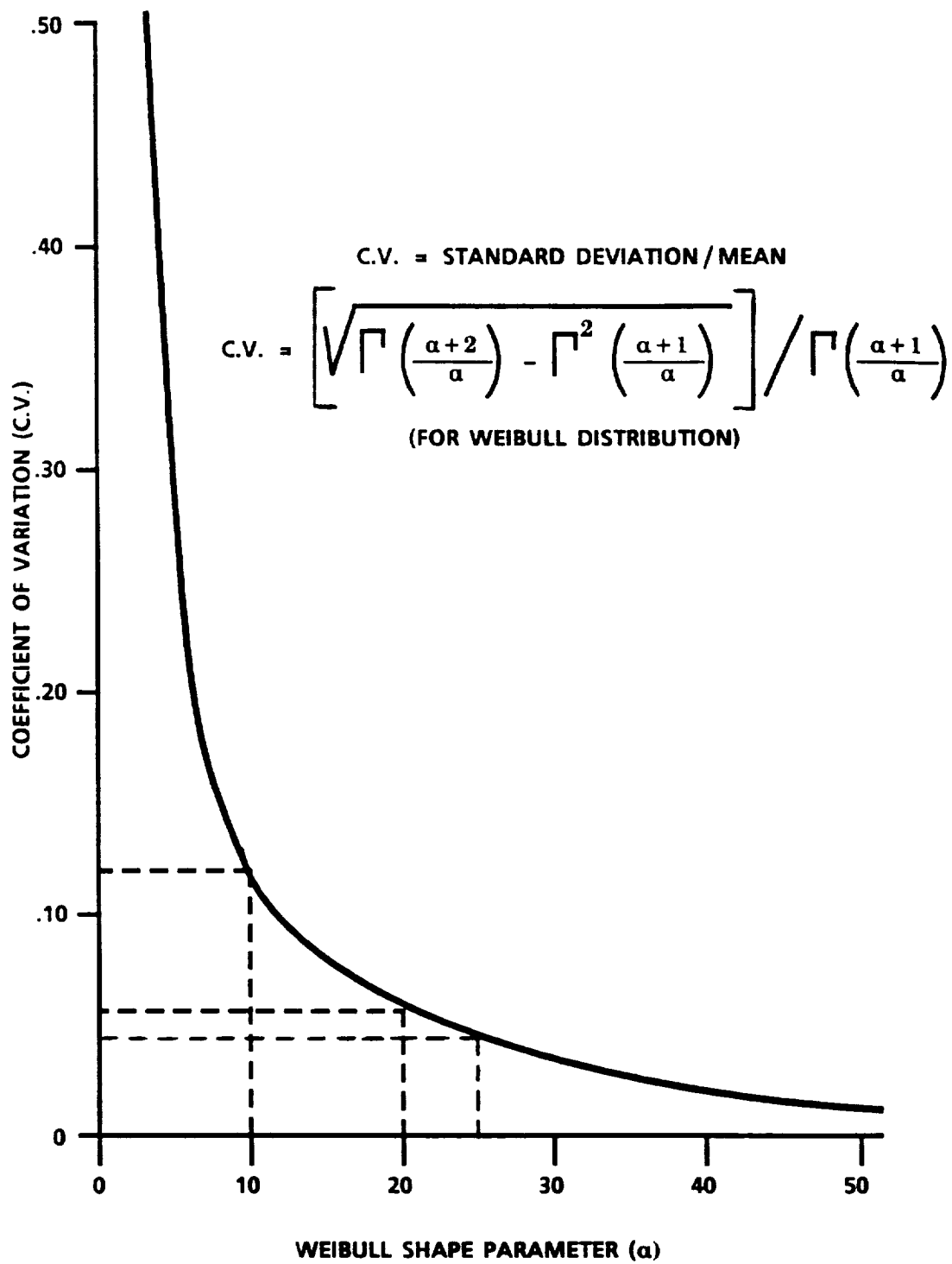


Figure 3. Coefficient of Variation Versus Weibull Shape Parameter

For an A-basis reliability (or probability of survival), $P = .99$; therefore:

$$\ln .99 = -\{[x/\bar{x}][.97844]\}^{25}$$

or, by solving for x/\bar{x} , which is the mean strength knockdown factor:

$$x/\bar{x} = [-\ln(.99)]^{.04}/.97844 = .85$$

TABLE II
STRENGTH VARIABILITY KNOCKDOWN FACTORS FOR METALS

Weibull Shape Parameter	Coefficient of Variation	A-basis K/D Factor	B-basis K/D Factor
40	3%	.90	.96
25	5%	.85	.93
K/D - Knockdown			

C. KNOCKDOWN FACTORS FOR COMBINED STRUCTURAL RESPONSE AND STRENGTH VARIABILITY

A-basis and B-basis knockdown factors, calculated for combined structural response variability (SRV) and strength variability (SV), are also listed in Reference 3 for several magnitudes of both variabilities. These factors were developed by using the two-parameter Weibull distribution to describe each variability.

Two sets of factors from Reference 3 are shown in Table III. The first set was based on the modal values of 19 and 20 for the SRV and SV Weibull shape parameters, from two groups of pooled data, and represents the most probable or "best" estimates for the knockdown factors. The second set was based on SRV and SV shape parameters of 10 and 8.8, respectively, which represent nearly minimum values for both shape parameters from the same pooled data groups; and therefore provide conservative estimates for the knockdown factors.

TABLE III
COMBINED SRV/SV KNOCKDOWN FACTORS FOR GRAPHITE-EPOXY

Weibull Shape Parameters SRV SV		Coefficients of Variation SRV SV		A-basis K/D Factors	B-basis K/D Factors
19	20	6.5%	6%	.75	.85
10	8.8	12%	13.3%	.55	.63

K/D - Knockdown

D. FACTOR OF SAFETY CONSERVATISM

Section IV.A indicates that the minimum acceptable factor of safety (FS) for graphite-epoxy composite structures varies between 1.5 and 3, depending on the adequacy of the data base and whether or not the design verification included full-scale testing to failure. It also notes that the referenced FS values are to be used with design allowables that already include knockdowns for environmental effects and strength variability (Design Approach 2 from Section II.B).

A method is needed for evaluating the conservatism of different graphite-epoxy FS values for structural design. However, for composites, a meaningful assessment is difficult to make, because the selection of FS values (to account for uncertainties, such as flaws, damage, and failure mode) is largely a matter of design experience. One approach that provides some qualitative information is to compare design margins for the strength of graphite-epoxy materials (allowable stress minus operating stress) with the design margin for the strength of a more predictable material such as aluminum (FS = 1.4 for spacecraft).

As indicated by Figure 1, the strength design margins for graphite-epoxy depend on the number and magnitude of the knockdown factors as well as on the desired FS value. For Design Approach 2, the design allowable (DA) can be expressed in terms of the mean strength (MS) and the knockdown (K/D) factors for environment (Envir.) and strength variability (SV) as follows:

$$\begin{aligned}
 DA &= MS - MS(1 - \text{K/D Factor for Envir.}) - MS(1 - \text{K/D Factor for SV}) \\
 &= MS(\text{K/D Factor for Envir.} + \text{K/D Factor for SV} - 1)
 \end{aligned}
 \tag{1}$$

The design allowable can also be written in terms of the operating allowable (OA) and the FS value as:

$$DA = FS \times OA \quad \text{or} \quad OA = DA/FS \quad [2]$$

Therefore, the strength design margin (SDM) for Approach 2 can be expressed as follows:

$$\begin{aligned} SDM &= DA - OA = DA - DA/FS = DA(FS - 1)/FS \\ &= MS(K/D \text{ Factor for Envir.} + K/D \text{ Factor for SV} - 1)(FS-1)/FS \end{aligned} \quad [3]$$

or, as a ratio of mean strength:

$$SDM/MS = (K/D \text{ Factor for Envir.} + K/D \text{ Factor for SV} - 1)(FS-1)/FS \quad [4]$$

Using SV knockdown factors from Tables I and II of Section IV.B, and assuming environmental knockdown factors of 0.8 for graphite-epoxy and 1.0 for aluminum, equation 4 can be evaluated for graphite-epoxy FS values of 3.0, 2.25, 2.0, and 1.5 as well as for an aluminum FS value of 1.4. These results are summarized in Table IV.

For the first three FS values, strength design margin ratios were determined for graphite-epoxy materials with coefficients of variation of both 12 percent and 6 percent. A coefficient of variation (C.V.) of 12 percent is typical of a graphite-epoxy material that is poorly defined or has poor quality control, while a C.V. of 6 percent represents a well-defined material with good quality. For the graphite-epoxy FS of 1.5, only one ratio was calculated (for a C.V. of 6 percent), since a FS of 1.5 does not provide an adequate strength margin at a C.V. of 12 percent. For the aluminum FS of 1.4, a single strength design margin ratio was determined for a C.V. of 5 percent, which is a typical value for this material. A sample calculation for the A-basis ratio of case 1a (Table IV) follows:

For a C.V. of 12 percent and A-basis reliability, Table I indicates that the S.V. Knockdown Factor is .645. Then, from equation 4:

$$\begin{aligned} SDM/MS &= (.8 + .645 - 1.0)(3.0 - 1.0)/3.0 \\ &= (.445)(2.0)/3.0 = .297 \end{aligned}$$

TABLE IV
COMPARISON OF STRENGTH DESIGN MARGIN RATIOS

Case	Material	Factor of Safety	C.V.	A-basis SDM/MS	B-basis SDM/MS
1a	G-E	3.0	12 %	.297	.405
1b	G-E	3.0	6 %	.403	.467
2a	G-E	2.25	12 %	.247	.338
2b	G-E	2.25	6 %	.336	.389
3a	G-E	2.0	12 %	.223	.304
3b	G-E	2.0	6 %	.303	.351
4	G-E	1.5	6 %	.202	.237
5	Al	1.4	5 %	.243	.266

SDM/MS = Strength Design Margin/Mean Strength
G-E = Graphite-Epoxy

By comparing the strength design margin ratios from Table IV, the following observations and conclusions can be made relative to graphite-epoxy FS conservatism:

1. A graphite-epoxy FS of 3.0 provides a substantially larger strength design margin than an aluminum FS of 1.4, over a wide range of material strength variabilities (6 percent to 12 percent). Therefore, a FS of 3.0 would provide adequate conservatism when used with Design Approach 2.
2. Graphite-epoxy FS values of 2.0 and 2.25 provide substantially larger strength design margins than an aluminum FS of 1.4, for 6 percent strength variability. However, for 12 percent variability, the A-basis margins are about the same. Therefore, FS values of 2.0 and 2.25 would provide adequate conservatism when used with Design Approach 2, except for cases where material strength variability is high and A-basis reliability is required.

3. A graphite-epoxy FS of 1.5 provides a smaller strength design margin than an aluminum FS of 1.4, even for 6 percent strength variability and B-basis reliability. Therefore, an FS of 1.5 may not provide adequate conservatism when used with Design Approach 2. This FS value appears more appropriate for use with Design Approach 3 or 4.

From the results of this section, it is apparent that FS conservatism is strongly dependent on: operating environment, material strength variability, and required material strength reliability.

V. STANDARDS

Industry-wide standards are required for material specifications, processing procedures, testing methodology, failure definition, and failure criteria to reduce the variability in composite properties. This need is being addressed by the following organizations.

A. MATERIAL SCIENCES CORPORATION

The Material Sciences Corporation (MSC), under the direction of the Army Materials Technology Laboratory (MR), is preparing a three-volume replacement for MIL-HDBK-17A, Part 1 (Reference 9). The title for this new document is Material Handbook: Polymer Matrix Composites. Volume I is subtitled: Guidelines (Reference 4); Volume II is subtitled: Material Properties; and Volume III is subtitled: Utilization of Data.

Volume I was published in February of 1988. An initial review indicates that this volume is probably the most comprehensive effort to date to provide a standard set of guidelines, but it is still incomplete. For example, Chapters 2 and 3, which cover the evaluation of fibers and matrix materials, have not yet been included. In addition, only B-basis reliability is used for the composite statistical properties. A-basis reliability is not addressed at this time. The information has been coordinated with the FAA, NASA, and the U.S. Armed Services. Several references to ASTM standards are also included. According to information from MSC, Volumes II and III should be published this year.

B. SOCIETY OF AUTOMOTIVE ENGINEERS

The Aerospace Materials Division of the Society of Automotive Engineers (SAE) has been active in the publication of three types of documents relating to specifications and information on composite materials. These documents have the following designation and content:

1. AMS - The Aerospace Materials Specification, which is the principal document used for procurement of materials.
2. AIR - The Aerospace Information Report, which is mainly a document to identify new materials and processes, and is not normally used for procurement purposes.
3. ARP - Aerospace Recommended Practices, which covers procedures and methods for identifying composite manufacturing techniques.

Reference 5 indicates that there are at least 120 SAE Standards relating to composites. Out of this number, about 25 percent are AMS Specifications that are listed in DODISS and ANSI.

C. AMERICAN SOCIETY FOR TESTING AND MATERIALS

The American Society for Testing and Materials (ASTM) Committee D-30 on High Modulus Fibers and Their Composites has been playing a key role in the development of rational test methodology for composites through Standards writing activities and symposia sponsorship. A large number of ASTM Standards for composites are listed in Reference 4.

D. SUPPLIERS OF ADVANCED COMPOSITE MATERIALS ASSOCIATION

The Suppliers of Advanced Composite Materials Association (SACMA) [located at 1600 Wilson Blvd., Arlington, Virginia] has had a special task force working to develop standards for Prepreg processing procedures and test methods for the past year and a half. Results of this effort should be ready for publication by the end of 1988. A new task force is currently being assembled to develop standards for carbon fiber composites.

E. ARMY MATERIALS TECHNOLOGY LABORATORY

A Composite Technology (CMPS) Program Plan has been developed under the auspices of the Army Materials Technology Laboratory (MR) to define the coordinated DOD management program for standardization in composites technology. The CMPS Standardization Area document (Reference 10) provides a comprehensive review of current standards development activities. These include: problems of the CMPS Area, proposed actions, ongoing projects, planned projects, completed projects, and organizations. In addition, this publication furnishes useful summaries on: composite materials, opportunities for composites technology, problems in composite technology, MIL and ASTM standards, SAE Specifications, SACMA recommended test methods, and military handbooks for nondestructive testing.

F. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (POLYMERS DIVISION)

The Polymers Division of the National Institute of Standards and Technology has published a draft standard for data bases on the identification of polymer matrix composite materials and for the reporting of test results (Reference 11). Two different types of data bases are defined: collection oriented and user oriented. Relationships of the draft standard to various groups concerned with composites are noted.

VI. CONCLUSIONS

1. For composite structures, factor of safety (FS) values vary with the adequacy of the test data base, the conservatism of the design allowable, whether or not the effects of knockdown factors have been included, and the method of design verification. Typical values for graphite-epoxy FS values can be grouped as follows:
 - **FS = 3**, if the data base of test results for material properties and failure modes is limited, and design verification does not include full-scale testing of the structure to failure.
 - **FS = 2 to 2.25**, if the data base of test results includes an adequate definition of material properties (as required by MIL-HDBK-17) and a complete description of failure modes (as determined by the "building block" approach), but design verification does not encompass full-scale testing of the structure to failure.
 - **FS = 1.5**, if the data base of test results includes an adequate definition of material properties (as required by MIL-HDBK-17) and a complete description of failure modes (as determined by the "building block" approach), and design verification does encompass full-scale testing of the structure to failure.
2. Composite FS values also vary with the designer's ability to analyze the structure (e.g., for complicated structures, where failure modes are difficult to predict, FS = 3 might be used versus 2.25, even though extensive test data were available). A larger than normal factor of safety might also be used on certain flight-critical components.
3. Composite FS conservatism strongly depends on operating environment, material strength variability, and required material strength reliability.
4. Composite strength knockdown factors (to account for variations in material composition, structure geometry, and service environment) are developed from test data using statistical analyses. Therefore, their values depend on sample size, data variability, and the level of reliability desired.
5. Typical mean strength knockdown factors for graphite-epoxy strength variability range from a very conservative 0.645 for high variability and A-basis reliability, to a nonconservative 0.901 for low variability and B-basis reliability. Typical knockdown factors for environmental effects are in this same range, and are the more important factors for materials with low to moderate strength variability.

6. The strength variability of composites is greater than that of metals. Therefore, composites require larger mean strength knockdowns for strength variability (smaller knockdown factors) to provide the same reliability. For example, a typical conservative B-basis knockdown factor for graphite-epoxy strength variability is 0.81, while an equivalent B-basis knockdown factor for aluminum is 0.93.
7. For composite materials, the design allowable can vary greatly for the same material and application, depending upon how much conservatism has been incorporated as a result of testing and analytical methods, strength limit definition, and knockdown factors.
8. The design of composite structures relies heavily on design-development testing and full-scale design-verification testing.
9. The material strength values for composite materials vary greatly with design application, fabrication process, and manufacturer.
10. To reduce the variability in composite properties, industry-wide standards are required for material specifications, processing procedures, testing methodology, failure definition, and failure criteria. This need is being addressed by several organizations.

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GLOSSARY

A-basis Reliability - The material strength value above which 99 percent of the population of values is expected to fall, with 95 percent confidence.

Advanced Composite - A type of composite material consisting of high-strength reinforcing fibers embedded in a metal, ceramic, or resin matrix. However, in this guide, the term "advanced composites" (or composites) has the more limited meaning of graphite or Kevlar fibers embedded in a thermosetting or thermoplastic resin matrix.

B-basis Reliability - The material strength value above which 90 percent of the population of values is expected to fall, with 95 percent confidence.

Composite - In general, an abbreviation for any composite material. However, in this guide, it implies an advanced composite material.

Composite Material - A combination of materials differing in composition or form on a macroscale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other. The component materials act in concert to achieve properties for the composite that are superior to the components taken separately. Normally, the constituents can be physically identified and will exhibit an interface between one another.

Compressive Ultimate Strength - Maximum material strength under compressive loading.

Coupon - A test specimen for material properties that has been carefully prepared to comply with a standard geometry.

Delamination - The separation of the layers of material in a laminate. This may be local or may cover a large area of the laminate. It may occur at any time in either the curing process or the subsequent life of the laminate, and may arise from a variety of causes.

Design Ultimate Load (DUL) - Maximum load that a structure has been designed to accept without failure. The DUL equals the DLL multiplied by the FS. In practice, the DUL is usually less than the Material Ultimate Load.

Design Limit Load (DLL) - Maximum expected operating load for a structure. The DLL usually represents a statistical worst-case load (e.g., a 1 in 100 probability of occurrence) rather than an absolute worst-case load. In practice, the DLL is usually less than the Material Limit Load.

Design Allowable (DA) - Allowable material strength for structural design under static loading conditions. The design allowable is established from coupon test data and can vary greatly for the same material and application, depending upon how much conservatism has been incorporated as a result of testing and analytical methods, strength limit definition, and knockdown factors.

Element - A test specimen that has been fabricated to represent a portion of the full-scale component or structure at a complicated loading area such as a bonded or bolted joint.

Environmental Effects - The degradation of composite material properties due to environmental factors such as temperature, moisture, and ultraviolet light.

Factor of Safety (FS) - A load multiplication factor that is applied to the maximum expected operating load (or design limit load) to provide a conservative design ultimate load for structural design.

Fiber - A general term used to refer to filament-based strands of materials. Often, fiber is used synonymously with filament. It is a general term for a filament of finite length.

Fiber-dominated Lay-up - A laminate test specimen (coupon) that has the majority of its reinforcing fibers oriented in the direction of the applied load.

Filament - The smallest unit of a fibrous material. The basic units that are formed during spinning, and gathered into strands of fiber (for use in composites). Filaments are usually of extreme length and very small diameter. Filaments normally are not used individually.

Fracture Toughness - The ability of a material to absorb energy in the fracture zone during loading. This is a measure of the resistance of a material to crack growth.

High-cycle Life - Component service life that is based on a large number of fatigue cycles.

Knockdown Factor - A material strength reduction factor that is applied to the material mean strength to account for variations in material composition, service environment, and structural geometry.

Lamina - A single ply or layer in a laminate.

Laminate - A product made by bonding together two or more layers (laminae) of the same or different materials.

Lay-up - A process of fabrication involving the assembly of successive layers of resin-impregnated material. Also, the composite material that is formed by this process.

Low-cycle Life - Component service life that is based on a small number of fatigue cycles.

Material Limit Load - This load corresponds to the proportional elastic limit load for the material under tensile loading.

Material Ultimate Load - This load is the maximum tensile load required to fail the material.

Material Strength - The maximum stress (tensile, compressive, or shear) that can be sustained by the composite material; or, because of the near linear relationship between composite stress and strain, the strain level existing under the maximum stress condition.

Matrix - The essentially homogeneous material in which the fiber system of a composite is embedded.

Matrix-dominated Lay-up - A laminate test specimen (coupon) that has the majority of its reinforcing fibers oriented in a direction normal to the applied load.

Maximum Operating Load - See design limit load (DLL).

Microcracking - The growth of microscopic cracks in the composite (resin) matrix under high-stress conditions. This failure process initiates at the matrix interface with the reinforcing fibers.

Modulus of Elasticity - The ratio of change in stress to change in strain below the elastic limit of a material. Also referred to as Young's Modulus.

Notched - Having an irregularity, such as a hole or a surface cut-out, which produces a stress concentration. Material test specimens (coupons) are notched with standard cut-outs to measure fracture toughness.

Notch Sensitivity - The tendency to fracture in the presence of a stress concentration. The material would possess low "fracture toughness." This also refers to sensitivity to fracture due to surface irregularities.

Operating Allowable - Material stress or strain level associated with the design limit load.

Poisson's Ratios - The absolute ratios of the transverse strains to the axial strain (below the proportional limit) for a condition of uniform axial stress.

Resin - A solid or pseudo-solid organic material, usually of high molecular weight, which exhibits a tendency to flow when subjected to stress. It normally has a softening or melting range, and fractures conchoidally. Originally resin referred to natural substances, but now is used as a generic term for polymeric materials. It is usually qualified to type, such as "thermoplastic resins."

Residual Strength - Material strength after a component or test specimen has undergone a number of fatigue cycles. The residual strength decreases as the number of cycles increase. However, composites retain a greater percentage of their original strength than metals.

Service Environment - The environment (temperature and moisture levels, chemical agents, etc.) in which a component must operate. Also referred to as the operational environment.

Shear Modulus - The ratio of stress to strain below the proportional limit for shear. Also referred to as Modulus of Rigidity.

Specific Stiffness - Modulus of Elasticity (or Shear Modulus) divided by the material density.

Specific Strength - Material strength divided by material density.

Strain - The change in length per unit length in a member, or a portion of a member, as the result of an applied load.

Strength - See material strength.

Strength Variability - Random differences in material strength for supposedly identical test specimens and loading conditions.

Strength Design Margin (SDM) - Excess strength that is designed into a structure by using a Factor of Safety. The SDM equals the design allowable stress minus the maximum operating stress, or it can also be expressed as the design allowable stress multiplied by the design margin.

Stress - Force per unit area. A measure of the intensity of the force acting on a definite plane passing through a given point. The perpendicular and parallel stresses acting on the plane are the normal and shear stresses, respectively.

Structural Response Variability (SRV) - Differences in stress or strain level at the same location in supposedly identical structures for the same applied load. SRV is caused primarily by fabrication tolerances.

Structural Response - Stress or strain level in a structure, resulting from an applied load.

Tensile Ultimate Strength - Maximum material strength under tensile loading.

Test Ultimate Load (TUL) - The failure load for a structure under test conditions.

Thermoplastic - A type of resin that can be repeatedly softened by heating and hardened by cooling, through a temperature range characteristic of the resin. When in the softened stage, it can be shaped into articles by molding or extrusion. A thermoplastic remains essentially a linear polymer in subsequent processing, and may flow without heat under mechanical pressure only.

Thermosetting - A type of resin that is essentially infusible and insoluble after having been cured by heat or other means. A thermosetting resin may first be made to flow like a thermoplastic before thermosetting. The distinguishing feature is the cross-linking of the polymer into a more rigid three-dimensional structure.

1. Report No. NASA CR-186010		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle A Guide to Structural Factors for Advanced Composites Used on Spacecraft				5. Report Date August 1989	
				6. Performing Organization Code	
7. Author(s) Robert Van Wagenen				8. Performing Organization Report No.	
				10. Work Unit No. Task #4100A	
9. Performing Organization Name and Address Vitro Corporation 600 Maryland Avenue, SW Washington, DC 20024				11. Contract or Grant No. NASW-4311	
				13. Type of Report and Period Covered Contractor Report	
12. Sponsoring Agency Name and Address Office of Safety, Reliability, Maintainability and Quality Assurance National Aeronautics and Space Administration Washington, DC 20546-0001				14. Sponsoring Agency Code Q	
15. Supplementary Notes Prepared under the direction of Michael A. Greenfield, Systems Assessment Division					
16. Abstract The use of composite materials in spacecraft systems is constantly increasing. Although the areas of composite design and fabrication are maturing, they remain distinct from the same activities performed using conventional materials and processes. This has led to some confusion regarding the precise meaning of the term "factor of safety" as it applies to these structures. In addition, composites engineering introduces terms such as "knock-down factors" to further modify material properties for design purposes. This guide is intended to clarify these terms as well as their use in the design of composite structures for spacecraft. It is particularly intended to be used by the engineering community not involved in the day-to-day composites design process. An attempt is also made to explain the wide range of factors of safety encountered in composite designs as well as their relationship to the 1.4 factor of safety conventionally applied to metallic structures.					
17. Key Words (Suggested by Author(s)) Factors of safety Composites Spacecraft			18. Distribution Statement Unlimited - Unclassified Subject Category 24		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified		21. No. of pages 40	22. Price A03	

